Energize Missouri: Algae-Based Renewable Energy Study

Task C
National and International Algal Biofuels Research, Resource and Industrial Assets

Final Report

For
Missouri Technology Corporation

MRIGlobal Project No. 110754.1-C

August 15, 2011

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For
Missouri Technology Corporation
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Jefferson City, Missouri 65102

Attn: Jason Hall

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Preface

This report was prepared for the Missouri Technology Corporation under a subgrant award to MRIGlobal and entitled "Energize Missouri: Algae-Based Renewable Energy Study," signed by Mr. Jason Hall, and dated February 28, 2011. Work was initiated in accordance with a work plan submitted and approved on March 11, 2011. The project team includes members from MRIGlobal, Washington University in Saint Louis, and the University of Missouri, Columbia.

The objective of the grant is to produce a study to help define the development and commercialization of algae as a fuel source that would be a valuable adjunct to the state energy plan. The study would emphasize the potential benefits to the state economy that a commercial algae industry could bring, opportunities for Missouri to become a leader in such an industry, and the policy steps and collaborations that the state could initiate to strengthen Missouri's leadership in this area. The study is divided into seven tasks plus a final report. This report is the results of Task C, which compared the Missouri-based assets to those in other states and countries.

This Task C study was authored by Jay Turner of Washington University in St. Louis (WUSTL) as Principal Investigator, and co-authored by John Murphy (WUSTL). The authors wish to acknowledge contributions by Bill Babiuch, Stanley Bull, Gregory Karr, and Thomas Grant (MRIGlobal). We also gratefully acknowledge conversations with Richard Sayre (Donald Danforth Plant Science Center), Tom Verry and Shelby Neal (National Biodiesel Board), Mark Wigmosta (PNNL) and Richard Axelbaum, Raymond Ehrhard, Mark Henson, and Himadri Pakrasi (WUSTL).

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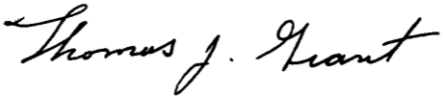

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Contents

Preface ii

Section 1. Introduction 1

Section 2. Domestic Assets—Regional Clusters 3
2.1 Southern California (San Diego) 3
2.2 San Francisco Bay Area/Silicon Valley 4
2.3 South Florida 5
2.4 Other 5

Section 3. International Assets 8
3.1 AlgaePARC (Wageningen, The Netherlands) 9
3.2 Israel 9
3.3 South Korea 10

Section 4. National-Scale Assessment of Biofuel Production Potential and Resource Demand 11

Section 5. References 14

Figures

Figure 1. Mean Annual Biofuel Production (L/ha-yr) Under Current Technology 12
Figure 2. Mean Annual Water Requirements (L/ha-yr) Under Current Technology 13

Tables

Table 1. Representative List of Companies Active in the Algal Biofuels Industry 6

Section 1.
Introduction

The Task A report provided an overview of the algal biofuels enterprise within the context of current and anticipated energy needs. Section 5 of that report briefly summarized Missouri's assets for the algal biofuels industry that were further elaborated on in Task B. This Task C report focuses on national and global assets, leading towards a critical assessment of Missouri's assets in Task D. For reasons described in the Task A report, the focus is on biodiesel production.

The Task B summary presented Missouri's assets that can (or could) contribute to the algal biofuels enterprise. Clearly, one of its greatest strengths is in research and development (R&D) where it is an acknowledged leader, particularly on the biology side. Another key asset for the State of Missouri is its significant presence in the biofuels—including biodiesel—industry. Missouri is home to a number of biorefineries that are processing primary, but not exclusively, soybean oil. The National Biodiesel Board (NBB) is headquartered in Jefferson City. NBB is an advocacy group for the biodiesel industry. As such, while it is a national organization the NBB staff is well positioned to assess the state's strengths, weaknesses, and needs. Further, NBB can be a valuable resource for perspectives on both successful and unsuccessful strategies in establishing and growing a biodiesel industry.

Algae 2020, a market research study of the industry by Emerging Markets Online, Inc., provides an excellent summary of the current status of the algal biofuel industry, and is the result of significant research, on-site visits, and interviews with a large number of participants in this field. The report includes a description of possible, future business models for the algal biofuels industry. Twelve potentially viable models are presented. In fact, in our team's discussions with a variety of experts, we found no consensus on a "best" model for developing a viable algal-based biofuel industry. Clearly, this industry is in its infancy, with immense potential and risk, and need for more clarity. An important conclusion from the *Algae 2020* assessment was that commercial success will require due diligence across a broad range of areas, including R&D, regulations and mandates, technologies, subsidies, and markets for both high value and low value (i.e., commodity) products.

As for Missouri's status in the algal biofuels enterprise, a *Biofuels Digest* 2009 readers' poll selected St. Louis the "King of Algae Energy" based primarily on its strength in research and much less on its strength in finance and as an "early stage company hotbed." San Diego, Seattle, and Silicon Valley rounded out the top four spots. In sharp contrast, the *Algae 2020* report highlighted three geographic regions—Southern California (San Diego), San Francisco/Silicon Valley, and South Florida—that are particularly notable hotbeds of activity for a variety of reasons. In addition, there are significant and important demonstration projects in New Mexico and Hawaii. This Task C report focuses primarily on these regions, highlighting the organization and scope of current activities.

The algal biofuels enterprise in the private sector tends to be dominated by relatively small companies that in many cases enter into (and often exit from) various forms of agreements with

larger companies. Examples include acquisitions, joint venture, and technology licensing. The motivation for these agreements is not always clear. For example, a small company engaged in algal biofuels R&D might be attractive to a larger biotechnology company not for the biofuels aspect *per se*, but rather for access to the company's algae biology with other applications in mind.

The approach taken in this report is to focus on geographic clusters of particularly high activity. In this sense, it is not a comprehensive inventory of national and international assets, but rather demonstrates the nexus of activities in key locations that are considered hotbeds for the industry. There are certainly additional R&D efforts outside of these clusters, but they are often a single or small group of researchers at an institution or a single company—large or small—that that are not woven into a network of local, synergistic activities. The algal biofuels R&D enterprise is dynamic; simple skimming the past few years of a trade journal such as *Biofuels Digest* reveals numerous start-up, expansion and collaborative activities. Understandably, it is more challenging to track the current status of such endeavors after they are launched, and divestment or the exit of companies from the enterprise tends to get less press.

There are exceptions such as the much-publicized January 2011, exit of Shell from Cellana, which was a joint venture between Shell and HR Biopetroelum. Cellana built and operates a marine algae biofuel demonstration facility in Hawaii. With this move, Shell no longer includes algal technologies in its bioenergy portfolio. Athough, in May 2011, Cellana received a $5.5 million grant from USDA and DOE to develop an animal feed supplement as a co-product to algal biofuels production, they need to make up the cost share of shell. Another confounding factor in inventorying R&D assets is that the activities of even relatively small companies can be quite spread out geographically and thus the location of their headquarters does not necessarily reflect the location of core R&D efforts. For example, Phycal is headquartered and has a "subpilot" (individual process level) R&D facility in the Cleveland area, has an algal biotechnology laboratory at the Bio-Research and Development Growth (BRDG) Park in St. Louis, and pilot algal farm in Hawaii.

In addition to covering key R&D activities, this report briefly summarizes one perspective on environmental resource assets that is conducive to large-scale algae cultivation. Wigmosta *et al.*, (2011) presented what is currently the most comprehensive national-scale assessment of algal biofuel production potential and resource demand.

Section 2.
Domestic Assets—Regional Clusters

2.1 Southern California (San Diego)

San Diego is the home to the "Big 4" algae culture labs: Sapphire Energy, Synthetic Genomics, Scripps Institute of Oceanography, and the San Diego Center for Algae Biotechnology at the University of California-San Diego. Sapphire Energy, founded in 2007 and headquartered in San Diego, is one of the most prolific algal biofuels companies with its primary lab in San Diego, engineering and project management offices in Orange County, a 22-acre R&D facility in New Mexico. It is currently building a 300-acre integrated algal biorefinery in New Mexico with claims to be in full-scale commercial production by 2018. The facility is being realized in large part because of $55.4 million in loan guarantees from the USDA Biorefinery Assistance Program. In March 2011, Sapphire and Monsanto entered into a collaboration to exploit Sapphire's algae-based research platform for improved genetic engineering of crops; this collaboration does not signal Monsanto's entry into the algal biofuels enterprise. Synthetic Genomics, founded in 2005 and based in La Jolla, is another prolific algal biofuels company. R&D efforts span a range of bioenergy areas. In the case of algal biofuels, its efforts are concentrated on an alliance with ExxonMobil with Synthetic Genetics focusing on improving algae strains and ExxonMobil focusing on the production aspects.

On the institutional side, the San Diego Center for Algae Biotechnology (SD-CAB)[1] was founded in 2008. Based at UC-San Diego, SD-CAB includes four institutional partners with 17 faculty researchers and is supported by eight corporate partners. Primary business activities of the corporate partners range from algal biofuels in particular (Sapphire) and renewable transportation fuels in general (Neste Oil) to biosciences (Life Technologies) and defense contracting (General Atomics). Four of these eight firms have a significant corporate presence in Southern California. The Center boasts a comprehensive platform of R&D activities with emphasis on algae biology. There is some focus on re-engineering of algae for coproducts production, algae cultivation in more diverse organism communities, and photobioreactor design and optimization. SD-CAB also owns a 40-acre test facility in California's Imperial Valley that includes 11 large (> 200,000 gallons) and 30 small raceway ponds to support its R&D efforts. This facility is operated by Biolight and the Carbon Capture Corporation. In 2010, the DOE awarded up to $9 million for the formation of the Consortium for Algal Biofuels Commercialization (CABC). This consortium, led by UC-San Diego, will focus on new approaches for algal protection, algal nutrient utilization and recycling, genetic engineering. University collaborators include UC-Davis, Rutgers and University of Nebraska. CABC is a participant in the Missouri-based U.S. National Alliance for Advanced Biofuels and Bioproducts (NAABB) which is based at the Donald Danforth Plant Science Center in St. Louis.

[1] http://algae.ucsd.edu/index.html

In summary, Southern California—the San Diego area in particular—can claim to be a hotbed for algal biofuels R&D with both companies that have significant traction and universities that are leaders in various aspects of the enterprise. The CABC and its focus on commercialization is a significant recent addition.

2.2 San Francisco Bay Area/Silicon Valley

The San Francisco Bay Area, like Southern California, is noted for its portfolio of both private and public sector activities in the bioenergy—including algal biofuels—area. The most prolific algal biofuels company in the area is Solazyme, founded in 2003, and located in South San Francisco, which focuses on an "indirect photosynthesis" route to algal oils production. Algae are grown using plant-based sugars and in the absence of light in fermentation tanks. The target product portfolio includes fuels, chemical, nutritionals, and the skin and personal care markets. In August 2011, Solazyme and Bunge Global Innovation announced a joint venture to construct an algal oil production facility in Brazil that will use sugars from local mills as a feedstock.

Several other companies in the area are focused on non-algal routes for biofuels production. Amyris, founded in 2003, and with headquarters in Emeryville, has developed a renewable diesel from lignocellulosic-derived sugar feedstocks. Using sweet sorghum as a feedstock, the company ferments the sugars and coverts the hydrogen produced in the fermentation into "green" diesel and other products. LS9, founded in 2005, and with headquarters in South San Francisco, is using a similar approach, but relies on a proprietary microbial catalyst to accelerate the process. LS9 raised $30 million by late 2010 from a variety of venture capital firms, including the capital venture arm of Chevron. The relative success of these two companies demonstrates that, while algal biofuels are certainly a focal area, there are other biofuels production routes that are attracting considerable interest and compete in the very competitive space for venture capital that is critical for start-ups.

In addition to corporate activity, the San Francisco Bay Area has substantial bioenergy R&D assets at its universities and other institutions. While there are some relevant activities at Stanford University, UC-Berkeley stands out for its programs such as the Joint BioEnergy Research Institute (JBEI), a DOE-funded Bioenergy Research Center.

While there has been a relatively long tradition of bioenergy R&D activities in the San Francisco Bay Area, a particularly noteworthy recent addition is the Lawrence Berkeley National Laboratory's Advanced Biofuels User Facility. In March 2010, LBNL received $18 million in stimulus funding through the DOE's Office of Energy Efficiency and Renewable Energy. The core facility will be the Advanced Biofuels Process Development Unit (PDU) to expedite the commercialization of next generation biofuels technologies. This public user facility will open in August 2011, in the San Francisco East Bay area. Its operations are focused on biofuels in general and not algae in particular.

In summary, while the San Francisco Bay Area is clearly a hub or activity in bioenergy R&D and this broad-based knowledge platform should not be discounted, with the exception of Solazyme it does not have a particularly active area for algae-based biofuels research.

2.3 South Florida

Algenol Biofuels, founded in 2006 and located in Bonita Springs, Florida, is an industrial biotechnology company with core business focused on algal biofuels. Their focus; however, is not on biodiesel production, but rather ethanol production. Algenol has partnerships with Dow Chemical to build a pilot-scale demonstration biorefinery in Texas, and with The Linde Group (a gases and engineering company) to develop and optimize carbon dioxide and oxygen management strategies for Algenol's algal biofuels technologies. In 2009, Algenol was awarded $25 million from DOW to build a pilot-scale integrated biorefinery in Lee County, Florida, again focusing on the algal-based ethanol production. Partners include Dow Chemical, the National Renewable energy Laboratory (NREL), Membrane Technology and Research (MTR), Georgia Tech, and the University of Colorado. Of the 27 award recipients in the DOE integrated biorefinery program, three are focused on algal technologies—Sapphire, Solazyme, and Algenol. This demonstrates the traction of these companies in the algal biofuels field.

PetroAlgae, founded in 2006 and headquartered in Melbourne, Florida, has developed a biocrude, which can be efficiently converted to diesel, jet fuel, and other fuel products in existing refinery infrastructure. Their approach uses open pond bioreactors and generates an animal feed co-product. PetroAlgae has laboratories in Melbourne and at the NASA Kennedy Space Center Life Sciences Laboratory (Cape Canaveral, Florida) and a field-scale R&D demonstration facility in Fellsmere, Florida. PetroAlgae's business plan is to license the technology to other companies rather than enter into production themselves.

These R&D efforts in Florida are assisted by a consortium of Florida universities which includes more than 50 faculty members from 11 member universities. In addition, the consortium has a working relationship with MRIGlobal to provide test beds for large-scale production prototypes. Some of the consortium researchers have been active in the field for more than 30 years.

In summary, Florida is often mentioned as a hotbed of algal biofuel R&D. This reputation is in large part because there is a strong private sector presence. Institutions such as the state's universities are also engaged, albeit not the breadth and depth taking place in San Diego.

2.4 Other

Beyond these three geographic clusters, there are additional activities spread throughout the U.S. that vary greatly in both focus and standing. Table 1 provides a representative list of companies active in the field. While the presence of the three geographic clusters is clear, they by no means account for the whole extent of domestic activities. For example, BioProcess Algae of Portsmouth, Rhode Island is using the carbon dioxide stream from an ethanol plant in

Shenandoah, Iowa, to produce algae for biodiesel and animal feed additives. The project has been proven conceptually and the project team estimates the 50 mgy ethanol plant can produce 3 mgy of biodiesel and 24,000 tons of high-protein meal products annually.

Table 1. Representative List of Companies Active in the Algal Biofuels Industry

Company	Location	Type of Activity
Sapphire Energy	San Diego, California	Algal biofuels; biorefinery under construction in New Mexico
Synthetic Genomics	San Diego, California	Genomic-driven solutions to develop green crude
LS9	South San Francisco, California	Fermentation-based technology to produce biofuels from feedstocks such as algae
Solazyme	South San Francisco, California	Manufacturer of algal-derived fuels
Algenol	Bonita Springs, Florida	Focuses on ethanol production from algae
PetroAlgae	Melbourne, Florida	Green diesel, gasoline and jet fuel from algae
BioProcess Algae	Providence, Rhode Island	Designs, manufactures and operates integrated bioreactor systems for algae production
Cellana (Shell and HR Biopetroleum)	Big Island, Hawaii	Hybrid photobioreactor-pond development and algae identification; Shell has recently divested from Cellana
Martek	Columbia, Maryland (with facilities in Colorado, Kentucky, South Carolina)	Algae fermentation - focused primarily on nutraceuticals including omega-3
Phycal	Cleveland, Ohio	Integrated production system with focus on algal oil
Phyco Biosciences	Chandler, Arizona	”Super Trough” algae production technology to compete with open pond raceways and photobioreactors
Solix Biosystems	Fort Collins, Colorado	Floating photobioreactors to provide an outdoor growth environment for algae
Virent	Madison, Wisconsin	Plant sugars to biofuels using a variety of feedstocks in including algae, investments from Shell and Cargill

Heliae, a private company located in Gilbert, Arizona, uses specialized proprietary strains of algae developed with researchers at Arizona State University in photobioreactors to grow algae that are subsequently used to produce a spectrum of products. Although they have a large effort on jet fuel, the company considers the multi-product strategy key to successful production models given the current markets and costs. Heliae received discretionary stimulus funding from the State of Arizona through Science Foundation Arizona (SFAz)—a public/private non-profit organization founded in 2006, to among several objectives, diversify and strengthen Arizona’s economy by investing in scientific and engineering areas deemed of high economic importance to the state.

Furthermore, there are other ongoing efforts to build *regional centers of activity*. One example is the Desert Biofuels Initiative started by Arizona State University. The Initiative is a Phoenix-based social venture aimed at advancing the development of a robust sustainable biofuels infrastructure in the Sonoran Desert region. Local companies active in algal-based fuels development include Phyco Biosciences, Diversified Energy, Desert Sweet Biofuels and Bye Energy, and Heliae.

A strong model for a *state-based collaboration* into the biofuels field is the Colorado Center for BioRefining and Biofuels, a cooperative research and education center located at the University of Colorado in Boulder.[2] Partner institutions include the Colorado School of Mines, Colorado State, and the National Renewable Energy Laboratory. Much of their work has been focused on plant-based biofuels, and the associated chemical and mechanical processes necessary to convert those feedstocks to fuels. However, they have moved into the algae field along with other researchers. An important aspect of the collaboration is that the universities, which have in the past competed for research dollars now coordinate their efforts and the hopes of achieving improved funding success.

While this section has focused on R&D assets, no discussion is complete without a survey of the many new organizations, formed within the past 5 years, which are active in promoting algal-based biofuels. These organizations are mentioned in no particular order; the intent is to demonstrate the increased interest this topic has attracted in the past few years. The *National Algae Association* was founded by a Houston investment banker and claims to be the first algae trade association in the U.S. It was created to assist entrepreneurs in creating commercial-scale algae production plants in the U.S. The *U.S. Algal Biomass Organization* was founded in Seattle by Boeing to promote the development of commercial markets for renewable and sustainable commodities derived from algae. The organization's membership of 64 companies includes most of the domestic algae R&D companies mentioned in this report along with other stakeholders such major transportation fuel consumers (e.g., FedEx, IATA). Finally, while not focused exclusively on algae, the National Biodiesel Board (NBB) headquarter in Jefferson City, Missouri, is interested in the full spectrum of biodiesel feedstocks including algae.

[2] http://www.c2b2web.org

Section 3.
International Assets

While most of the current algal biofuel R&D is based in the United States, there are considerable activities, especially focused on high value-added products around the globe. Most of the activities are centered in Europe, which comes as no surprise because private sector R&D is often linked to universities or other research institutions (e.g., spinoffs from university research). A major initiative is underway in Europe to organize all aspects of the algae enterprise. In January 2009, the European Commission (EC) funded the "AquaFUELs"—a project spearheaded by the European Biodiesel Board (EBB) to establish "the state of the art on research, technological development, and demonstration activities regarding the exploitation of various algal and other suitable non-food aquatic biomasses for 2nd generation biofuels production." The EC provided nearly 750,000 euro for this project which was completed in June 2011 with a final report pending; several interim deliverables are available.[3] AquaFUELs activities have centered on assessments and surveys; several subtasks have contributed to the body of knowledge about the state of the algal biofuels enterprise, highlighting what is needed to move forward along the pathway to commercialization.

Another major AquaFUELs initiative was to form the European Algae Biomass Association (EABA). Headquartered in Florence, Italy, the EABA's objectives are: to promote mutual interchange and cooperation in the field of biomass production and use, including biofuels uses and all other utilizations [...]; creating, developing, and maintaining solidarity and links between its members and at defending their interests at European and international level [...]; and to act as a catalyst for fostering synergies among scientists, industrialists, and decision makers in order to promote the development of research, technology, and industrial capacities in the field of algae. EABA was officially launched at its first conference this summer and currently has 38 industrial members from 16 countries and 32 scientific members (academic and other institutions) from 12 countries.

AquaFUELs has also significantly contributed to the inventorying of relevant R&D assets around the globe. A December 2010, report (AquaFUELs, 2010) compiled a directory of 419 stakeholders—mostly in Europe and the United States, but with global representation—including 212 industrial stakeholders and 187 research/academia stakeholders (often individuals). For each industrial stakeholder a precise description of the company's interest was sought, including a self-designation as a technology provider, producer, or end user. The 194-page directory is publically available and is an excellent, if necessarily incomplete, resource. Focusing on the industrial stakeholder, 88 are in Europe, 86 in the United States, and 38 in other countries. Most of the European industrial stakeholders are based in Belgium, Spain, Germany, France, Italy, and the Netherlands although most European countries have a presence. Outside of Europe and the United States, the industrial stakeholders are primarily in Australia, Israel, Japan, Taiwan, and India with four-to-five stakeholders in each country.

[3] http://www.aquafuels.eu/.

Our analysis of the European industrial stakeholder directory demonstrates a strong emphasis on R&D, especially technologies using closed photobioreactors, to cultivate algae for high value-added products such as nutraceuticals and pharmaceuticals. *Virtually no companies engaged in R&D or production mentioned biofuels except in the context of being a long term objective consistent with their short term activities*. This is consistent with the recent algal biofuels outlook by Wijffels *et al.*, (2010) which concludes that "10 to 15 years is a reasonable projection for the development of a sustainable and economically viable process for the commercial production of biofuels from algal biomass."

Outside of Europe and the United States, current industrial R&D assets are few, but this could quickly change, particularly if government incentives are provided. Several recent conferences (e.g., the 1st International Conference on Algal Biomass, Biofuels, and Bioproducts; St. Louis, July 2011) had very strong attendance from countries outside Europe and the United States. The remainder of this section highlights three activities to provide examples of the international assets that should be viewed not so much as competition, but as a platform for potential collaborations.

3.1 AlgaePARC (Wageningen, The Netherlands)

The Algae Production and Research Centre (AlgsePARC), based at Wageningen University, has considerable traction in the area of algal biofuels R&D. The center focuses on identifying and addressing scale-up issues that present barriers to industrial commercialization for a variety of application in including biodiesel production. Indeed, their stated goal is "to fill the gap between fundamental research on algae and full-scale algae production facilities." Research is funded by the provincial government and numerous companies. Projects include, but are not limited to, photobioreactor design, algae growth optimization (e.g., photosynthetic efficiency, oxygen inhibition), systems biology for the production of high value-added products, and engineering feasibility studies.

3.2 Israel

Israel was among the first countries with substantial industrial R&D activities in the algal biofuels area. In many cases, these companies are capitalizing on biology and engineering initially developed at the country's universities. Most companies are focused on nutraceuticals production. TransAlgae is a U.S. registered company with R&D operations in Israel. Founded in 2008, the company focuses on genetic engineering with additional core competencies in production and harvesting processes. As part of their vision for industrial symbiosis, they envision aquaculture and poultry industries developing near algae production facilities to take advantage of the coproduct streams rather than necessarily choosing algae production sites that already have such industries already in place. This suggests a target market of developing countries growing needs for both food and fuels. Alga Technologies primarily focuses on expanding a spectrum of nutraceutical and cosmaceutical products that can be produced form algae. Closed tubular reactors are used to cultivate algae under conditions that maximize astaxanthin production. Algaenesis focuses on sunlight utilization technologies to optimize algae

production with stated emphasis on the nutraceuticals market. However, few details about the company are available.

The most prolific Israeli company in the algal enterprise is Seambiotic. Founded in 2003, Seambiotic focuses on coproduction of omega-3 and biofuels. For more than 5 years they have operated an R&D pilot plant in Israel with 1,000 m^2 of ponds that is coupled to the flue gas from a power plant. A 10 hectare open pond commercial facility is being built in China, and is scheduled to open in September 2011. While Seambiotic is based in Israel, it chose China for its first commercial production facility in part because of available land near water and CO_2 resources and relatively cost of construction materials and labor.

3.3 South Korea

South Korea has a strong tradition of R&D leading to commercialization. One internationally-recognized institution is KAIST (formerly the Korea Advanced Institute of Science and Technology), which is the country's premier center for strategic R&D. The Advanced Biomass R&D Center at KAIST has a significant research thrust in biofuels, biorefineries, and allied technologies. For example, for the past 5 years Professor Ji-Won Yang and colleagues have been working on algae cultivation to capture CO_2 from power plant flue gases and using the algae to produce biofuels. This work builds upon more than 15 years of applied research by this group into various aspects of industrial symbiosis such as of using wastewater as source of nutrients for algae cultivation. KAIST has additional expertise in algae biology that complements these projects. EcoPhyco Tech is a South Korean industrial R&D stakeholder, not included the AquaFUELs directory, that has patented an engineering algae strain that can capture CO_2 with high efficiency and is tolerant to pollutant commonly present in coal-fired power plant flue gases. The Professor Choul-Gyun Lee group at Inha University is also internationally recognized in algae cultivation, especially using photobioreactors. Much of the South Korean R&D is focused on marine algae, but this does not necessarily present a barrier to productive collaborations.

Section 4.
National-Scale Assessment of Biofuel Production Potential and Resource Demand

Section 2 summarized domestic regions that have developed into real or perceived hotbeds for algal biofuels—and more generally bioenergy—research and development. However, the regions that have received the most attention for demonstration and commercial facilities are not strictly collocated with these R&D hubs. Arizona, New Mexico, and West Texas have attracted the most attention to date for such facilities. Key rationale appears to be the abundance of flat land—in many cases of marginal value for crop production—and warm climates. Water resources are a potential concern for operations at the commercial scale, and these areas would likely rely upon saline and brackish waters to the extent they do not cause problems in the algae growth, harvesting and extraction processes.

A national scale perspective on algal biofuel production and resource demand was recently published by Wigmosta *et al.* (2011). This assessment begins to chip away at the conventional notions for the optimal siting of facilities. While the analysis necessarily made several assumptions concerning current and future technologies and did not address the availability of resources (carbon dioxide, nutrients, and especially water), it is a significant step forward in presenting a national perspective. The modeling assumed land currently in cultivation was not available for algae production. As described in the Task A and Task B reports, this took most of Missouri—including the Bootheel region—out of play because certain climate, terrain, and water resource conditions that are favorable to algae production are also favorable to agriculture and these areas are in cultivation. This stands in sharp contrast to the Southwest U.S. (Arizona, New Mexico, and West Texas) where cultivation has taken place to a significant, but more limited extent, in large part due to the lack of suitable water resources. At the foundation of the Wigmosta *et al.* (2011) analysis—which focuses on open pond bioreactors—is an algae biomass growth model that depends on several factors with sunlight and pond temperature being the key parameters driving geographic differences in algae productivity. To drive the algae growth model, pond temperature is estimated from a hydrodynamic and water quality model that accounts for heat exchange (including evaporation) at the pond surface. Evaporation rates from this model are used together with precipitation rates to determine consumptive water use.

Results were presented for nearly 12,000 hypothetical 500 ha ponds that passed the initial land use and flat terrain screening criteria. Mean annual theoretical maximum algae production ranged from ~ 100,000 to 125,000 L/ha-yr of algal oil in the northern latitudes to 140,000 to 165,000 L/ha-yr in the southern latitudes. These differences are significant, but perhaps not as large as might have been expected. Figure 1 shows mean biofuel production (L/ha-yr) under current technology for the modeled hypothetical pond locations. Current technology production rates are much lower than the theoretical maximum values, which demonstrates room for improvement. Highest production is for low elevation regions in the south and lowest production is for high elevation regions in the north; this pattern is consistent with the length of the growing season as driven by the pond temperature. *Using mean annual biofuel production as the sole figure of merit*, south Texas and Florida are most attractive followed by the greater Gulf Coast area, central Texas, and portions of southern Arizona and southern California. The next higher

latitude band of north Texas, Oklahoma, and Arkansas lag not far behind and it is quite possible that portions of southern Missouri, such as the Bootheel, would be in the range of 5,000 to 6,000 L/ha-yr. Approaches to extend the growing season—such as the use of waste heat from a power plant to keep ponds warm in the winter, as demonstrated by researchers at Lincoln University—could narrow productivity differences between Missouri and the more favorable regions to the south.

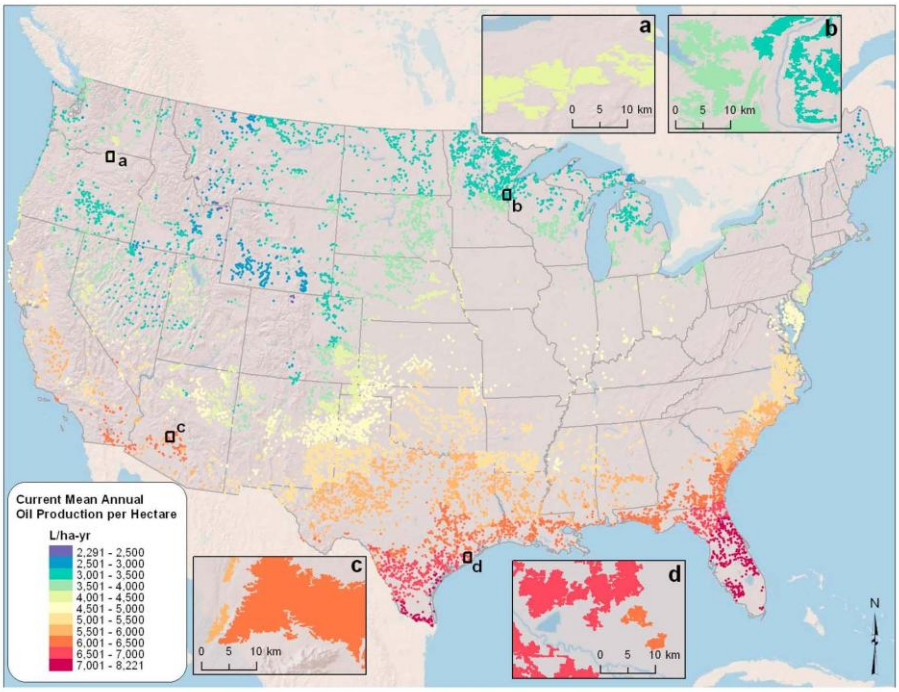

Figure 1. Mean Annual Biofuel Production (L/ha-yr) Under Current Technology
(From Wigmosta *et al.* 2011)

Algae productivity is by no means the sole figure of merit for identifying areas most attractive for commercialization. Water resources are another important consideration. Figure 2 shows the mean annual water requirements using current technology as estimated by Wigmosta *et al.* (2001). Water demands are relatively high in the southwest U.S., which is precisely the region that has received the most attention for algae cultivation. Presumably the rationale is that certain algae strains can tolerate high salt loadings and other contaminants found in saline and brackish water. However, from the perspective of the entire algae-to-biofuels production process it is possible that technology innovations will be needed to lessen the effect of such contaminants on the post-growth processing steps. Wigmosta *et al.* (2011) also demonstrated that the nationwide pattern for water intensity of algae production (i.e., the liters of consumptive water use per liter of biofuel produced) qualitatively tracked the water requirements patterns shown in Figure 2.

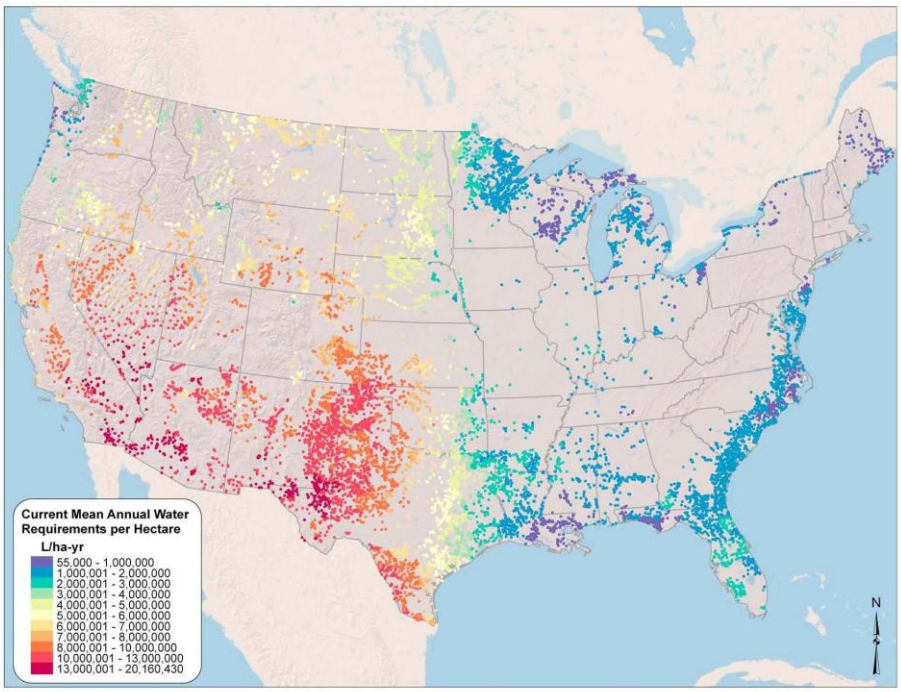

Figure 2. Mean Annual Water Requirements (L/ha-yr) Under Current Technology
(From Wigmosta et al. 2011)

The national scale assessment of algae productivity and water resource demand provides an important but only partial evaluation of the relative merits for siting production facilities in various geographic locations. These findings must be integrated with *resource availability* data such as CO_2 sources, nutrient supplies, and water. Task B highlighted some of these assets (e.g., power plants, wastewater treatment plants) in the State of Missouri; it is beyond the scope of this project to inventory such assets nationwide. However, the integration of available resources is the next step in refining this national scale assessment and Wigmosta and colleagues are indeed actively working on this task. A critical subsequent step would be an assessment of cost in including land (which can carry an opportunity cost) and production.

In summary, the analysis presented by Wigmosta *et al.* (2011), represents the most comprehensive assessment available of landscape and climate assets that factor in algal biofuels production using algae growth in open ponds. The sunlight-rich region of the southwest U.S. does not have as clear of an advantage as is often perceived and its favorability for development of commercial-scale facilities depends to a large extent on the ability to use saline or brackish waters to meet most of the water resource demands.

Section 5.
References

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